

NASA Contractor Report 187545

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1989 HIGH-SPEED CIVIL TRANSPORT STUDIES

SUMMARY

(NASA-CR-187545) THE 1989 HIGH-SPEED CIVIL
TRANSPORT STUDIES SUMMARY REPORT (Douglas
Aircraft Co.) 24 p. OCLC 010

NP1-010

unclas

03/05 0650094

**HSCT Concept Development Group
Advanced Commercial Programs**

**MCDONNELL DOUGLAS CORPORATION
Douglas Aircraft Company
Long Beach, California**

**Contract NAS1-18378
September 1991**



National Aeronautics and
Space Administration

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ABSTRACT

This summary report contains the results of the Douglas Aircraft Company system studies related to high-speed civil transports (HSCTs). The tasks were performed under a 1-year extension of NASA Langley Research Center Contract NAS1-18378.

The system studies were conducted to assess the environmental compatibility of a high-speed civil transport at a design Mach number of 3.2. Sonic boom minimization, exterior noise, and engine emissions have been assessed together with the effect of laminar flow control (LFC) technology on vehicle gross weight.

The general results indicated that (1) a sonic boom loudness level of 90-PLdB at Mach 3.2 may not be achievable for a practical design, (2) the high-flow engine cycle concept shows promise of achieving the sideline FAR Part 36 noise limit but may not achieve the aircraft range design goal of 6,500 nautical miles, (3) the rich-burn/quick-quench (RB/QQ) combustor concept shows promise for achieving low EINO_x levels when combined with a premixed pilot stage/advanced-technology high-power stage duct burner in the P&W variable-stream-control engine (VSCE), and (4) full-chord wing LFC has significant performance and economic advantages relative to the turbulent wing baseline.

FOREWORD

The High-Speed Civil Transport Study Phase IIIA was a 1-year extension of the previous 2 years' work (Phases I to III). Phase IIIA was a combined technical research activity and systems evaluation covering the period from 1 October 1988 to 30 September 1989.

Work was accomplished as a task order activity by Douglas Aircraft Company in Long Beach, California. This work was under the direction of the NASA Langley Research Center, Hampton, Virginia, and was jointly funded under Contract NAS1-18378.

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GLOSSARY

alt	Altitude
ASME	American Society of Mechanical Engineers
D ₁	Destination
DAC	Douglas Aircraft Company
dB	Decibel (Reference Pressure Re. 20 μ Pa)
DIA	Diameter
EINO _x	NO _x Emissions Index (lb NO _x per 1,000 lb fuel burned)
EPNdB	Unit of Effective Perceived Noise Level
F	Fahrenheit
FAR	Federal Aviation Regulations
F _n	Thrust per Engine
fps	Feet per second
ft	Feet
ft ²	Square Foot
GE	General Electric Aircraft Engines
HSCT	High-Speed Civil Transport
IATA	International Air Transport Association
ICAO	International Civic Aviation Organization
ISA	International Standard Atmosphere
lat	Latitude
lb	Pounds
L/D	Lift-to-Drag Ratio
LFC	Laminar Flow Control
long	Longitude
LPP	Lean premixed prevaporized
MLW	Maximum Landing Weight
MSEC	Millisecond
MTOW	Maximum Takeoff Weight
NASA	National Aeronautical and Space Administration
NASP	National Aerospace Plane
N MI	Nautical Miles
NO _x	Oxides of Nitrogen (all species)
N-Wave	Basic sonic boom waveform, so called because it resembles an “N”
O ₁	Origin
OEW	Operator's Empty Weight
psf	Pounds per Square Foot
P&W	Pratt & Whitney

PLdB	Stevens Mark VII Perceived Level of Loudness in Decibels
PM/PV	Premixed/Prevaporized
RB/QQ	Rich-Burn/Quick-Quench
SL	Sea Level
S_{ref} and S_w	Wing Reference Area
TAD	Technology Availability Date
TAS	True Airspeed
TBE	Turbine Bypass Engine
TOFL	Takeoff Field Length
TOGW	Takeoff Gross Weight
typ	Typical
VCE	Variable Cycle Engine
VSCE	Variable-Stream-Control Engine
2-D	Two Dimensional
°C	Degrees Centigrade
Δp	Overpressure
ϕ_i	Equivalent Ratio (local fuel per air ratio to stoichiometric ratio)
τ	Rise Time

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SECTION 1 INTRODUCTION

This report presents a summary of the prime results of studies conducted as part of a continuing Douglas and NASA effort to determine the technologies required for the next-generation supersonic transport. This work (Phase IIIA) represents an extension of the 2 previous years' activities (Phases I through III) covering technical, environmental, and economic aspects of the HSCT. These previous phases led to focused studies to find a solution to the environmental issues of sonic boom, exterior noise, and engine emissions. Laminar flow control (LFC) technology was studied to determine the impact on vehicle gross weight reduction (fuel burn reduction), including installation requirements such as ducting, pumps, etc.

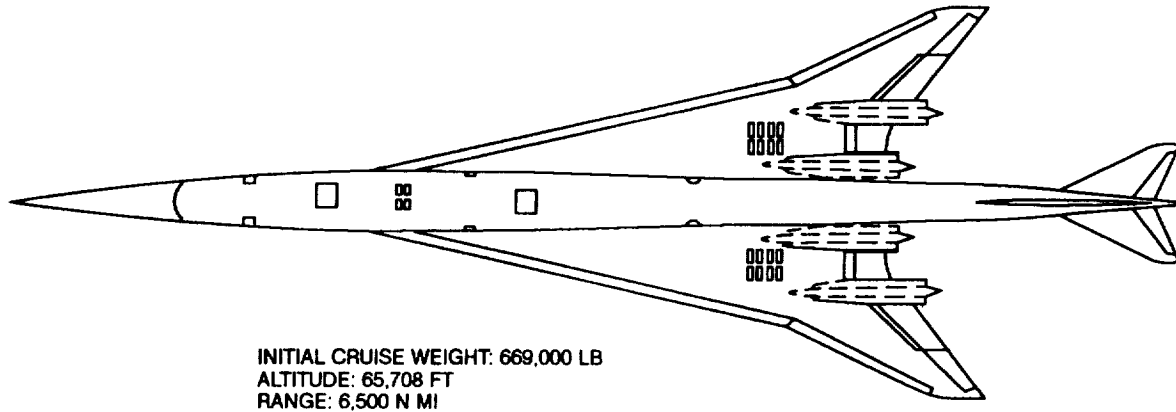
During earlier phases conducted by Douglas under NASA contract, conceptual vehicle definitions were developed over a range of Mach numbers from 2 to 25 (employing fuels from Jet A to hydrogen). In particular, the commercial value, mission performance, environmental compliance, and technology requirements were evaluated. This led to the following conclusions:

- Market projections for the 2000 to 2025 time period indicate sufficient passenger traffic for ranges beyond 2,000 nautical miles to support a fleet of economically viable and environmentally compatible high-speed commercial transports. Fleet needs, considering a 300-seat aircraft, could total 1,500 or more by 2025.
- The Pacific Rim area will become the major traffic region after the year 2000, leading to a design range objective of 6,500 nautical miles.
- Economic viability places emphasis on environmentally acceptable overland supersonic flight. The constraint of no overland supersonic flight reduces potential aircraft productivity and thus increases aircraft operating costs.
- Aircraft productivity increases with cruise speed up to about Mach 5 to Mach 6 for market applications ranging from 2,000 to 6,500 nautical miles. Above this point, the relative significance of cruise speed diminishes, and productivity is virtually constant.

SECTION 2

SONIC BOOM MINIMIZATION STATUS

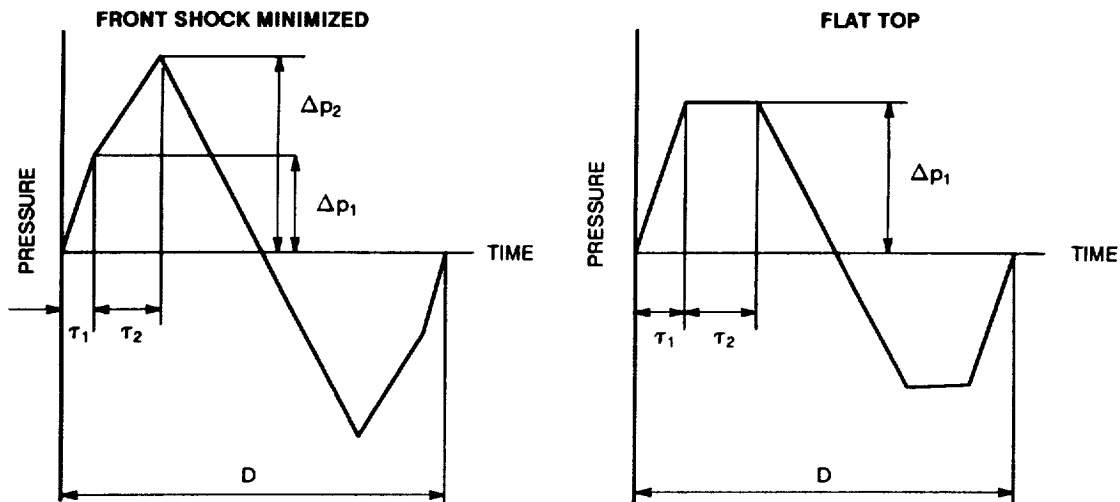
A tentative sonic boom loudness acceptability goal of 90 PLdB (0.6 psf) was selected based on human response data analyzed by Wyle Laboratories under contract to Douglas. The baseline Mach 3.2 configuration (D3.2-3A) shown in Figure 1 produces a classical N-wave overpressure on the ground during supersonic cruise overflight, resulting in a front shock of 1.9 psf or a loudness level of 102 PLdB. This represented a formidable technical challenge of achieving a 12-PLdB reduction in loudness.



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FIGURE 1. D3.2-3A BASELINE CONFIGURATION

Two different approaches are used to minimize sonic boom loudness. The first and most straightforward approach is to minimize the initial pressure disturbance at the aircraft source. The second approach, called waveform shaping, developed as researchers became more familiar with sonic booms and the mechanisms by which booms annoy or startle people. Typical so-called "minimized" waveforms are depicted in Figure 2.



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FIGURE 2. MINIMIZED SONIC BOOM WAVEFORMS

Vehicle design studies using the N-wave minimization technique were not successful in significantly reducing the loudness level. Therefore, the main effort was concentrated on the waveform shaping

method, which progressed to a point where the loudness of the Mach 3.2 configuration was reduced from 102 PLdB to 96.5 PLdB. The minimized configuration (D3.2-12) incorporated a canard into the design and removed the horizontal tail, as shown in Figure 3. This configuration was designed to achieve a front shock minimized waveform on the ground. The actual waveform shape achieved is shown in Figure 4 together with the baseline N-shape waveform. A major problem with the D3.2-12 was the poor low-speed performance resulting from its relatively small wing area, low aspect ratio, and high sweep angle.

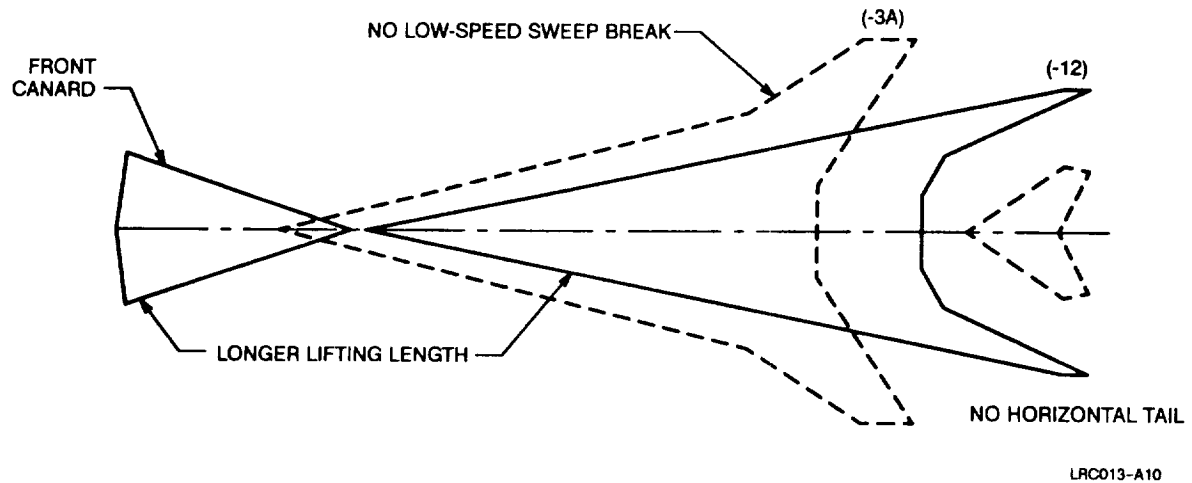


FIGURE 3. COMPARISON OF D3.2-12 AND D3.2-3A PLANFORMS

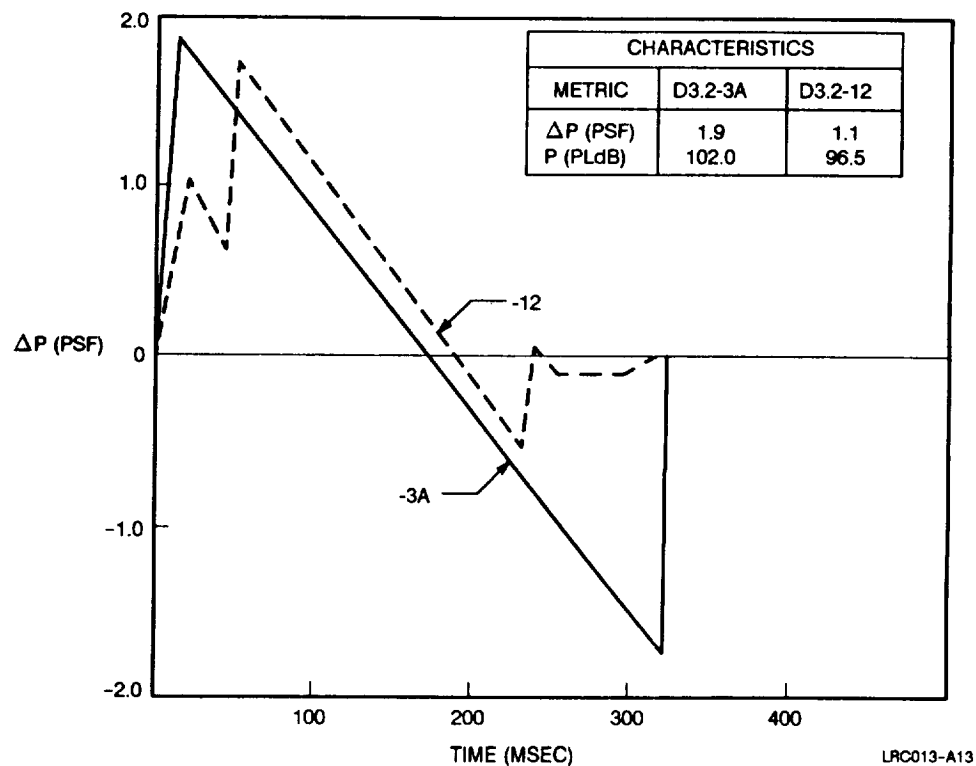


FIGURE 4. COMPARISON OF -12 AND -3A WAVEFORMS

SECTION 3

EXTERIOR NOISE STATUS

During Phase IIIA, studies have continued with the engine companies to assess HSCT engine cycles and noise suppression hardware that will comply with the current subsonic noise certification limits for new aircraft, FAR Part 36, Stage 3, and ICAO Annex 16, Chapter 3. This noise goal was established during previous HSCT system studies. However, Douglas recognizes two other exterior noise goals that are considered necessary to achieve HSCT environmental acceptance — airport noise and climb-to-cruise noise.

Community noise requirements for HSCTs at international airports should be compatible with the long-range subsonic aircraft that will be operating after the turn of the century. It may be necessary to develop automated noise abatement procedures that will minimize the HSCT airport noise impact. Secondly, it is also recognized that HSCT community noise, below the flight paths during takeoff climb phases to the cruise condition, should be compatible to that created by the existing fleet.

To evaluate the achievement of the above exterior noise goals, two noise reduction concepts have been explored in parallel:

- High-specific-thrust engines incorporating noise suppressors.
- High-flow engines with high exhaust mass flow and noise-suppression devices.

Both GE and P&W supplied engine cycle data and noise suppression hardware information for these concepts. The level of noise suppression used in the noise assessment was jointly determined with the engine companies.

The effects of engine sizing to achieve a 6,500-nautical-mile range with a standard day takeoff field length (TOFL) of 10,600 feet (11,000 feet for an ISA + 10°C acoustic reference day) have been evaluated for the maximum engine power codes (setting) for each engine cycle. All engine configurations have also been evaluated at fixed takeoff weight, landing weight, altitude, and engine thrust conditions to determine the level of acoustic technology achieved.

Both GE and P&W provided acoustic and performance data for a number of engines. The Phase IIIA engines all assumed a year 1995 engine technology availability date (TAD) corresponding to a year 2005 certification date. The following Mach 3.2 engines were studied:

- GE21/F14, Study M1, augmented variable-cycle engine (VCE).
- GE21/FLA1, Study A1, two-stream exhaust, nonaugmented high-flow fan VCE.
- GE21/FLA1, Study A2, three-stream exhaust, nonaugmented high-flow fan VCE.
- P&W STF947 augmented variable-stream-control engine (VSCE), both with the baseline convergent-divergent ejector nozzle with chute suppressor and with a high-flow mixer/ejector nozzle.
- P&W STJ950 single-spool nonaugmented turbine bypass engine (TBE) with a convergent-divergent ejector nozzle with chute suppressor.

The engine cycles described above used combinations of noise suppression hardware described in Table 1.

TABLE 1
NOISE SUPPRESSION HARDWARE

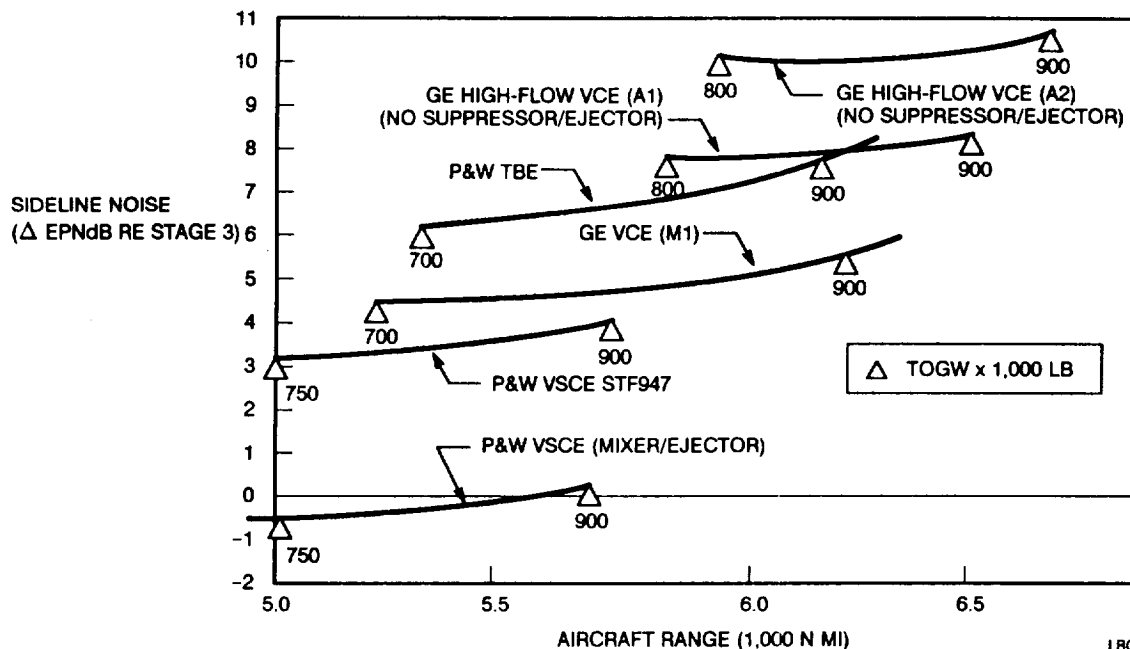
ENGINE CONCEPT	INVERTED VELOCITY PROFILE	DUCT STREAM SUPPRESSOR	SINGLE-STREAM SUPPRESSOR	MIXER/EJECTOR NOZZLE	ACOUSTICALLY LINED EJECTOR
GE STUDY M1 VCE	YES	YES	NO	NO	YES
GE STUDY A1 VCE	YES	NO	NO	NO	NO
GE STUDY A2 VCE	YES	NO *	NO	NO	NO
P&W TBE	NO	NO	YES	NO	YES
P&W VSCE	YES	YES	NO	NO	YES
P&W VSCE (MIXER/EJECTOR)	NO	NO	NO	YES	YES

*SUPPRESSOR WEIGHT WAS INCLUDED FOR AIRCRAFT SIZING PURPOSES

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All six engines were installed on the D3.2-3A configuration and the aircraft was sized to meet the following constraints: (1) takeoff field length of 10,600 feet for an ISA day, (2) landing approach speed of approximately 140 knots, and (3) cruise at optimum altitude or at the operationally determined ceiling (4,000-feet-per-minute potential rate of climb).

The sizing results regarding sideline noise and aircraft range are shown in Figure 5. The P&W VSCE achieved the sideline noise limits at ranges up to 3,500 nautical miles. Other engines succeeded in achieving higher ranges but were significantly above the Stage 3 noise limit.



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FIGURE 5. EFFECTS OF AIRCRAFT SIZING ON SIDELINE NOISE AND RANGE

To evaluate engine acoustic technology efficiency (e.g., engine cycle and noise suppression devices) realistic aircraft/engine parameters and assumptions were selected from previous mission performance and sizing analyses (see Table 2). The results of the acoustic technology noise screening estimates relative to the Stage 3 noise limits are given in Table 3.

TABLE 2
AIRCRAFT/ENGINE ACOUSTIC TECHNOLOGY SCREENING ASSUMPTIONS

(ISA + 10° C)			
	SIDELINE	TAKEOFF	APPROACH
MTOW/MLW (LB)	800,000	800,000	420,000
NET THRUST AT 1,000 FT (LB)	59,000	—	—
NET THRUST AT 1,200 FT (LB)	—	40,000	—
NET THRUST AT 400 FT (LB)	—	—	10,000
AIRCRAFT SPEED (KNOTS) TAS	201	201	168

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TABLE 3
SUMMARY OF ACOUSTIC TECHNOLOGY SCREENING RESULTS

JET NOISE Δ EPNdB RE. STAGE 3 LIMIT			
ENGINE	SIDELINE	TAKEOFF	APPROACH
P&W TBE	+6 (-12)	+6.5 (-11)	-7.5 (0)
P&W VSCE	+3* (-14)	3* (-12)	-3.5 (0)
P&W VSCE (MIXER/EJECTOR)	-1 (0)	—	—
GE STUDY M1 VCE	+4 (-14)	+2 (-12)	-3 (0)
GE STUDY A1 VCE	+7 (-3)	+3 (-2.5)	-9.5 (0)
GE STUDY A2 VCE	+9 (-4.5)	+6 (-3.5)	-6 (0)
747-400 (TOTAL NOISE)	-2 TO -3	-4 TO -6	0 TO -2

* INCLUDING DUCT BURNER NOISE CONTRIBUTION

() NOISE SUPPRESSION INCREMENT OTHER THAN ENGINE CYCLE EFFECT SUPPLIED BY
ENGINE COMPANIES FOR PROPOSED SUPPRESSOR CONCEPTS

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It is important to evaluate the noise impact at international airports of adding HSCTs to the world fleet. The current 747-400 noise certification level range of three certificated engine types show levels below Stage 3 limits. Therefore, for the HSCT to attain airport noise levels compatible to those of the 747-400, it may be necessary to develop automated minimum noise abatement procedures during takeoff and approach.

SECTION 4 ENGINE EMISSIONS STATUS

A major environmental consideration in propulsion technology is engine emissions and the resulting impact on atmospheric ozone. During Phase IIIA, the primary focus was to continue the fleet model fuel burn and annual emissions studies started in the previous system studies, to evaluate updated engine emissions data provided by the engine companies and to track and identify any significant trends or factors that could result in lower total emissions per flight.

During the current studies, emissions data for the Phase III (1988) STF905 VSCE, along with the corresponding fuel burn data, were extended to a model of total worldwide HSCT fleet annual emissions of those constituents that have been identified as having some possible effect on the environment (e.g., oxides of nitrogen, oxides of sulfur, water vapor, etc.). These data were released to NASA for input into an atmospheric model to evaluate the worldwide atmospheric impact.

Two combustor concepts being considered by the engine companies to minimize NO_x production are shown in Figure 6. The concepts are the rich-burn/quick-quench/lean-burn (RBQB) and the lean/premixed/prevaporized (PM/PV) combustors. The design goal is to produce a low- NO_x combustor producing an emissions index EINO_x of 3-8 pounds of NO_x per 1,000 pounds of fuel burned.

The process used to develop the two-dimensional (2-D) fleet model of total worldwide annual emissions for the 10 most heavily traveled IATA regions is illustrated in Figure 7 for a given region. Three engine emission data sets were produced for the P&W STF905 VSCE having a current-technology combustor, RBQQ, and LPP combustors. Eight emission exhaust product sets including NO_x were produced for each combustion type. A further improvement to the STF905 VSCE regarding NO_x production has recently been evaluated. In this case, a premixed pilot stage was added to the duct

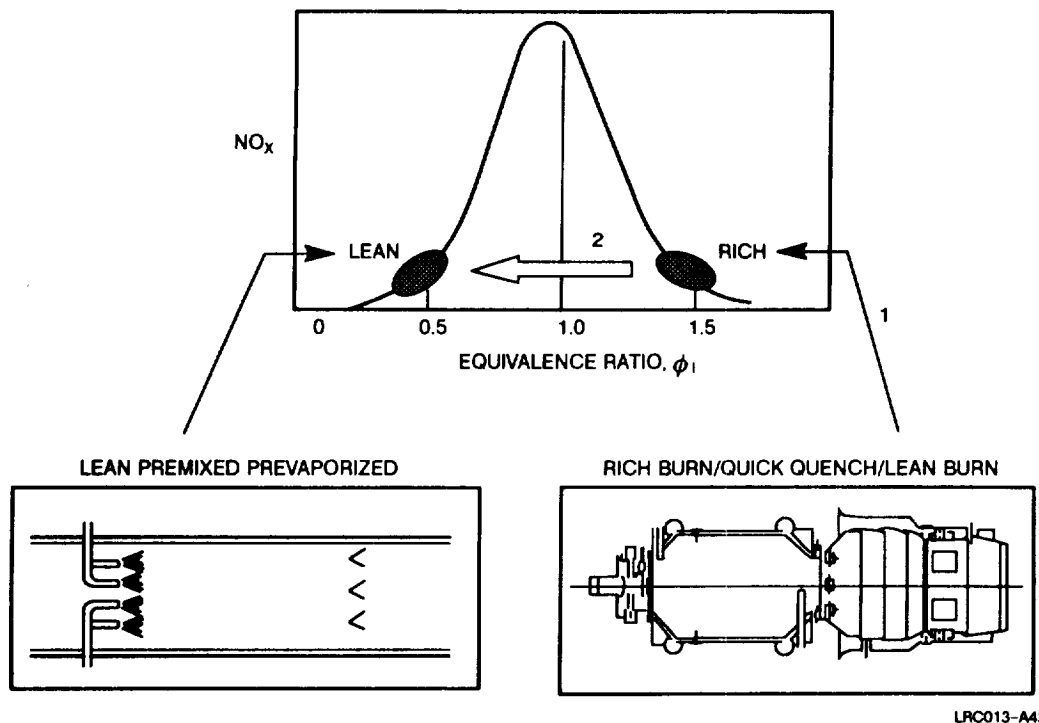
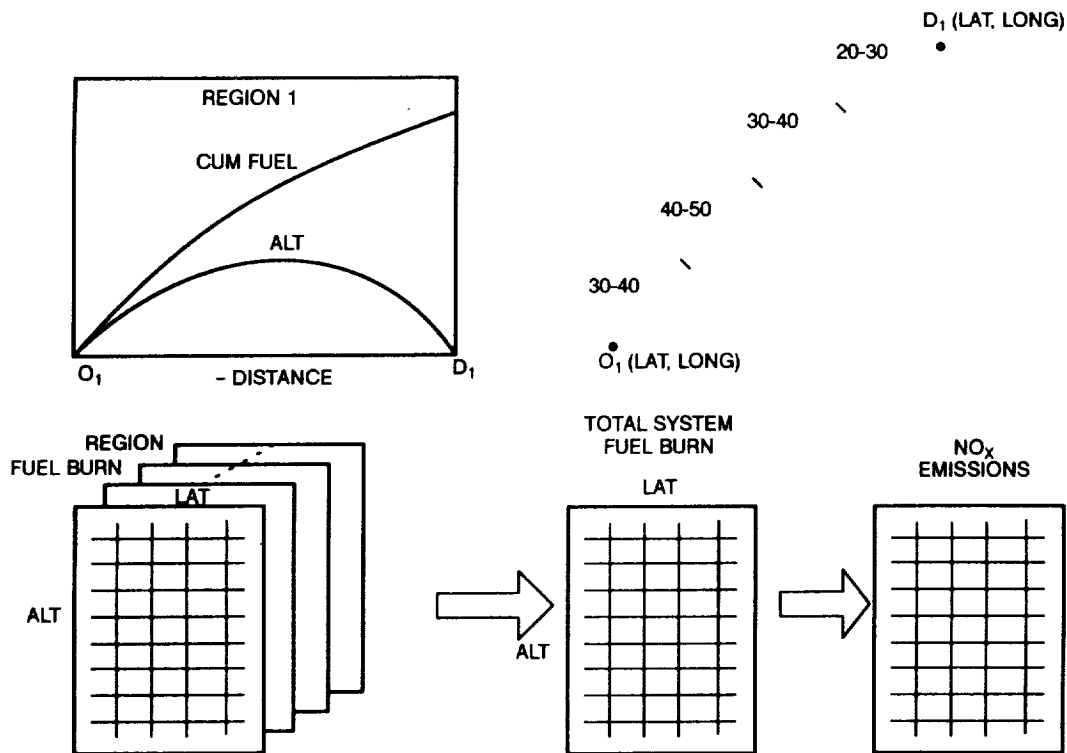


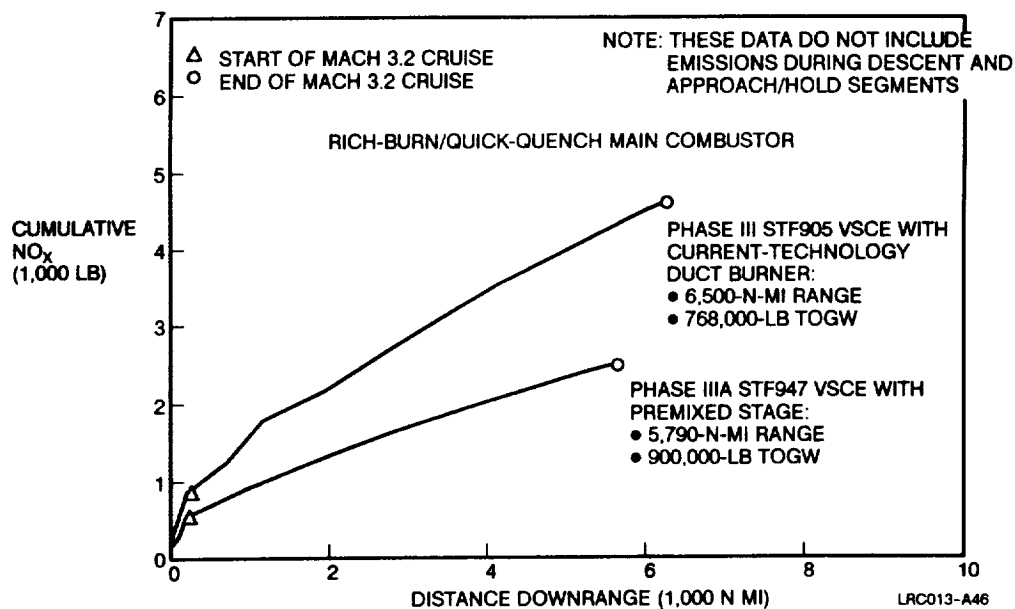
FIGURE 6. VARIATION OF NO_x WITH EQUIVALENCE RATIO



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FIGURE 7. HSCT FLEET MODELS - NO_x

burner, which reduced total emissions by almost 50 percent despite the aircraft's burning more fuel. This is shown in Figure 8 as STF947 VSCE.



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FIGURE 8. P&W VSCE NO_x EMISSIONS PER FLIGHT

SECTION 5 LAMINAR FLOW CONTROL (LFC)

A preliminary engineering integration design study of LFC was conducted, leading to an economic assessment. LFC, with its associated reduction in drag and additional weight and complexity, was applied to a fully turbulent version of the D3.2-3A configuration. To quantify the achievable benefit, the method of laminarization chosen was boundary layer suction through a perforated wing skin. Three configuration concepts were addressed. Two of the configurations used the -3A planform and thickness distribution with suction (1) outside the fuel tank boundary and forward of the control surface hinge line (partial LFC), and (2) forward of the control surface hinge line (full LFC). The two configurations are illustrated in Figure 9. The third configuration studied was an all-supersonic leading edge wing planform with full LFC. A comprehensive study was conducted involving an aerodynamic redesign of the -3A wing, suction system design, material selection, structural design, integration of the suction system, weight assessment, and mission performance evaluation. The final assessment of the LFC configurations was an economic evaluation based on the results of the engineering analysis.

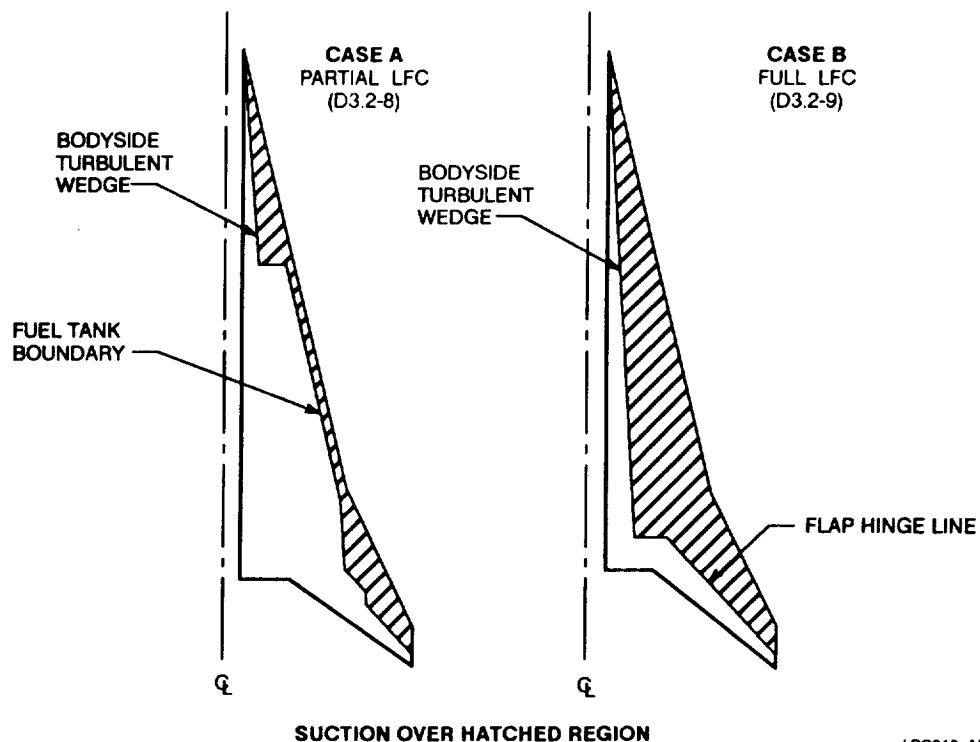


FIGURE 9. HSCT D3.2-8 AND -9 PLANFORM

A new wing section was designed based on the D3.2-3A planform at the cruise point, using the Euler code FLO67 (Reference 1). Since the suction system weight is directly related to the amount of suction required, the objective of the LFC design was to minimize the amount of suction required to laminarize the wing. This was achieved by generating wing sections that deliver a pressure distribution with minimum chordwise pressure gradient.

The suction system power requirements regarding the compressors were sized with separate systems for the upper and lower surfaces due to different flow rates and pressures. The system was sized for

start of cruise, or Mach 3.2 at 65,700 feet. The compressor sizes, weights, and power requirements were obtained from a potential supplier based upon the system requirements. Because of specific speed considerations, centrifugal compressors have been selected, with the relatively large size dictating two compressors per side (i.e., left and right), per surface, resulting in a total of eight compressors for the airplane. For the sizing studies, it has been assumed that the compressors are driven by electric motors (electric power from generators used to drive aircraft systems) and are located in the lower aft fuselage area. The penalty associated with the electric power is accounted for in the drive system weight.

The structural-material concepts that were analyzed were skin-stringer, superplastic-formed/diffusion-bonded, and honeycomb structures utilizing advance metal matrix composites. In evaluating these concepts, consideration was given to fail-safe design, damage tolerance, maintainability, and producibility.

The integration of the LFC suction system into the wing and fuselage structure was investigated for both suction cases. The LFC system was subjected to low-density 500° to 600° F air, which was ducted to the compressors with the least possible reduction in wing fuel capacity. The integration of the LFC system is shown in Figure 10. In addition, the system allows for the articulation of the leading edge flap panels.

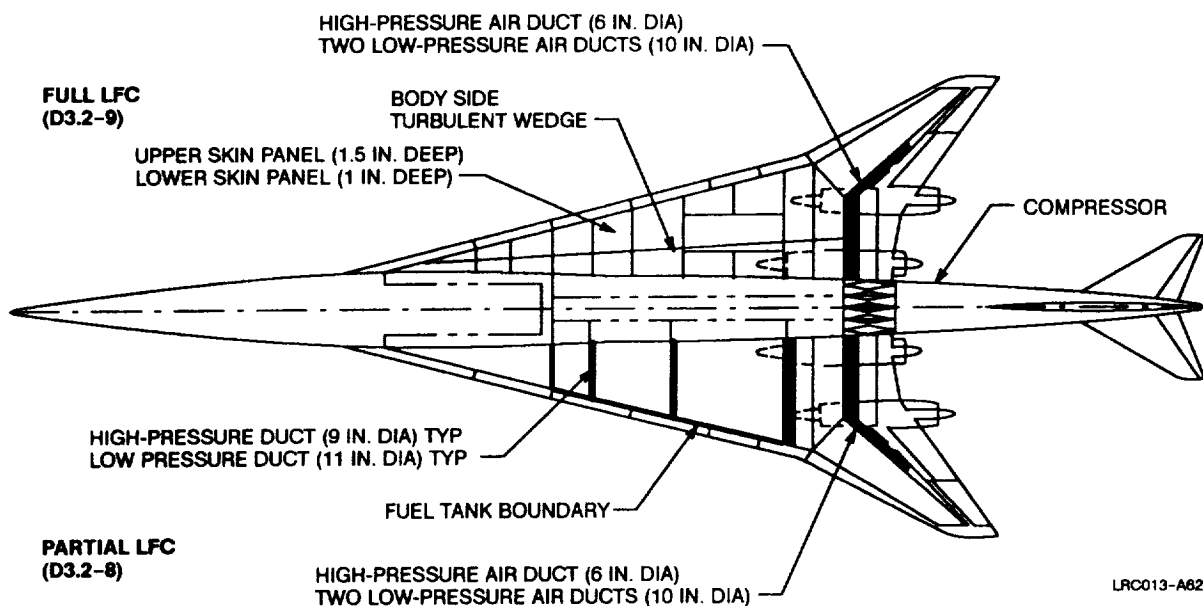


FIGURE 10. MACH 3.2 LFC TRANSPORT

A comprehensive weight analysis was conducted to develop the aircraft weight changes caused by the materials/structural changes and suction system. Weights for each of the LFC concepts were incorporated into a baseline to determine the new operating empty weight (OEW). The LFC-equipped aircraft were then parametrically evaluated for mission performance and resized.

A mission performance analysis was conducted for the three cases. The results are shown in Table 4.

An economic assessment was conducted which addressed the aircraft worth and flyaway cost of a vehicle having partial and full LFC relative to the turbulent baseline D3.2-3A. Flyaway prices and

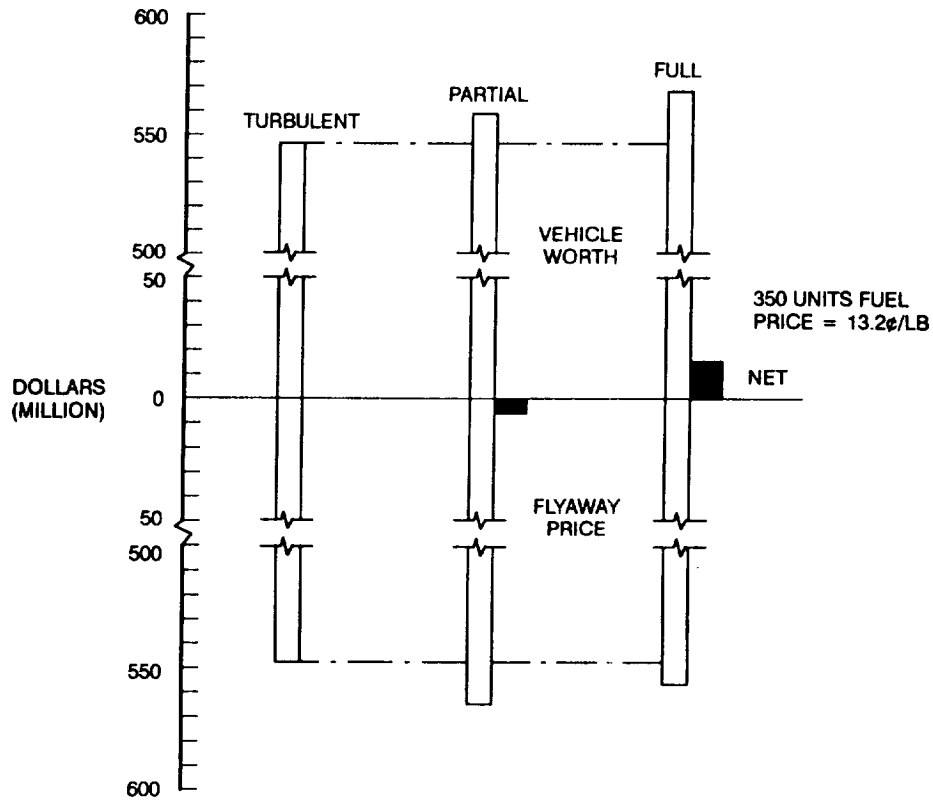
TABLE 4
HSCT D3.2-7/D3.2-8/D3.2-9 SIZE AND PERFORMANCE COMPARISON

	FULLY TURBULENT D3.2-7	PARTIAL LFC D3.2-8	FULL LFC D3.2-9
TOGW (LB)	835,500	799,500	767,384
Fn (LB)	70,323	65,955	62,139
OEW (LB)	240,673	248,025	249,674
BLOCK FUEL (LB)	477,920	438,053	408,803
L/D AVG	8.40	8.97	9.35

TOFL = 10,600 FT, RANGE = 6,500 N MI
 SL STANDARD DAY
 $S_w = 9,500 \text{ FT}^2$

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vehicle worth are shown in Figure 11 for the turbulent, partial LFC, and full LFC configurations. The greatest potential for net economic benefit lies with the full-chord LFC concept.



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FIGURE 11. ECONOMIC ASSESSMENT OF LFC

SECTION 6 CONCLUSIONS

The following is concluded from the studies conducted in the environmental areas of sonic boom, exterior noise, and engine emissions:

- **Sonic Boom** — Neither aircraft operational techniques nor minimization of N-wave type sonic boom signatures will be sufficient to achieve acceptable sonic boom loudness levels. Novel concepts such as vehicle shaping with significant lift carried forward are required to lower sonic boom levels for the Mach 3.2 configuration. The lowest level obtained in this study by waveform shaping was a perceived loudness of 96.5 PLdB.
- **Exterior Noise** — Of the six engine cycles considered in this study, none achieved both the aircraft range and noise goals.

GE None of the GE engines met the noise goal. The GE Study A2 three-stream and Study A1 two-stream high-flow fan engines were the only engines to achieve the 6,500-nautical-mile range goal at reasonable takeoff weights, but were 7 to 9 EPNdB above the Stage 3 sideline noise limits. An exhaust noise suppressor will be required for these engines.

P&W None of the P&W engines, which included a high-specific-thrust cycle with a noise-suppression system and an engine with a high-flow exhaust nozzle, met the aircraft range goal. However, the P&W VSCE with a mixer/ejector did achieve Stage 3 goals at a range of approximately 5,500 nautical mile.

- **Emissions** — For the P&W VSCE, the rich-burn/quick-quench combustor combined with a premixed pilot stage in a conventional duct burner shows promise of significantly reducing NO_x levels. This combustor technology has reduced risk levels relative to concepts studied previously according to engine company determinations.
- **Laminar Flow Control** — With regard to the potential for gross weight reduction through laminar flow control technology, the full-chord LFC concept proved to be preferable over fully turbulent and partial LFC concepts from both engineering and economic considerations. LFC also offers sonic boom, engine emissions, and exterior noise advantages by virtue of lower gross take-off and cruise weights.

SECTION 7 RECOMMENDATIONS

Based on the activities summarized in this report, it is recommended that the following technology developments be conducted to continue the significant progress accomplished in Phase IIIA:

- **Sonic Boom** — Continue the sonic boom waveform shaping studies, concentrating on the vehicle integration and flying qualities of the aircraft. Lower cruise speed characteristics and the development and implementation of higher order methodologies applied to unique planform shapes and engine exhaust simulation must be emphasized. The prospect of minimizing annoyance at Mach numbers less than 3.2 should be investigated. Human response studies to determine acceptable boom metrics and levels must continue to establish timely design requirements.
- **Exterior Noise** — The P&W mixer/ejector noise reduction concept should be studied for both the VSCE and TBE, and weight and noise reduction characteristics should be established by analysis and test. Studies of alternative GE and P&W high-flow engine cycles incorporating a suppressor should continue. Operational procedures and high-lift devices to minimize community noise using these advanced engines and suppression devices should be incorporated in future studies.
- **Engine Emissions** — Total annual fleet fuel burn emission scenarios and atmospheric modeling techniques to determine ozone impact and criteria should be emphasized during further studies. The development of low-emission combustor technology should continue and simultaneous trade studies should be conducted assessing engine emission and aircraft performance to minimize total emissions per flight and reduce risk.
- **The LFC integration studies** should be continued to validate in more detail the results achieved in Phase IIIA. Selection of the appropriate suction compressors and ducting requires more study.
- **Small-scale coupon testing** of various aircraft structural materials should be conducted to establish a data base appropriate for high-temperature porous surfaces required for the HSCT. Several innovative structural design concepts for the vehicle should be identified and evaluated to establish the minimum weight and maintenance combination.
- **Low-speed high-lift devices** will be essential to reduce community noise under the takeoff and approach flight paths. Innovative low-speed concepts with high L/D should be identified; low-speed wind tunnel tests should be conducted for promising high-lift devices.
- **Studies to reduce fuselage turbulent drag** should be initiated. These need to include aircraft wing resizing for maximum reduction in fuel and weight.
- **Detailed economic trade studies** should be conducted to cover the environmental technology areas affecting sonic boom, engine emissions and exterior noise.

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4. Title and Subtitle 1989 High-Speed Civil Transport Studies -- Summary				5. Report Date September 1991	
				6. Performing Organization Code	
7. Author(s) HSCT Concept Development Group				8. Performing Organization Report No.	
				10. Work Unit No. 537-01-22-01	
9. Performing Organization Name and Address McDonnell Douglas Corporation Douglas Aircraft Company 3855 Lakewood Blvd. Long Beach, CA 90846				11. Contract or Grant No. NAS1-18378	
				13. Type of Report and Period Covered Contractor Report	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665-5225				14. Sponsoring Agency Code	
15. Supplementary Notes NASA Langley Contracting Officer Technical Representative: Donald L. Maiden					
16. Abstract This summary report contains the results of the Douglas Aircraft Company system studies related to high-speed civil transports (HSCTs). The tasks were performed under a 1-year extension of NASA Langley Research Center Contract NAS1-18378. The system studies were conducted to assess the environmental compatibility of a high-speed civil transport at a design Mach number of 3.2. Sonic boom minimization, exterior noise, and engine emissions have been assessed together with the effect of laminar flow control (LFC) technology on vehicle gross weight. The general results indicated that (1) achievement of a 90-PLdB sonic boom loudness level goal at Mach 3.2 may not be practical, (2) the high-flow engine cycle concept shows promise of achieving the sideline FAR Part 36 noise limit but may not achieve the aircraft range design goal of 6,500 nautical miles, (3) the rich-burn/quick-quench (RB/QQ) combustor concept shows promise for achieving low EINO _x levels when combined with a premixed pilot stage/advanced-technology high-power stage duct burner in the P&W variable-stream-control-engine (VSCE), and (4) full-chord wing LFC has significant performance and economic advantages relative to the turbulent wing baseline.					
17. Key Words (Suggested by Author(s)) High-Speed Civil Transport Sonic Boom Exterior Noise Engine Emissions LFC			18. Distribution Statement Unclassified - Unlimited Subject Category 05		
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified		21. No. of pages 22	22. Price A03	

